

Prospective Life Cycle Design Enhanced by Computer Aided Process Modeling: A Case Study of Air Conditioners

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ABSTRACT

Prospective life-cycle design of emerging technologies is important in discussions of decarbonization and resource circulation strategies. This study demonstrates the role of computer-aided process engineering in reflecting technology information with appropriate granularity and accuracy using air conditioning as a case study. Process simulations involving heat exchangers (indoor/outdoor units), compressors, and expansion valves were developed to model air conditioners to quantify changes in performance and heat exchanger size as existing and alternative refrigerants are introduced. The process simulation results were incorporated into a material flow analysis and life cycle assessment to quantify the change in life cycle greenhouse gas (GHG) emissions through 2050 for each refrigerant installed. The results show that operational emissions dominate the life cycle GHG emissions of air conditioners, that decarbonization of electricity can significantly reduce life cycle GHG emissions, with similar results regardless of which refrigerant is used, and that differences in design policies when alternative refrigerants are introduced strongly affect the breakdown of emissions in 2050.

Keywords: Life Cycle Analysis, Interdisciplinary, Modelling and Simulations, Process Design.

INTRODUCTION

The prospective life cycle design of emerging technologies, combined with Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Input-Output Analysis (IOA), plays an important role in the design of sustainable societies and business strategies[1]. However, prospective life cycle design is usually not seamlessly linked to technological development. In the example of air conditioners, state-of-the-art development takes place for each component, including the development of new refrigerants and mixture of existing refrigerants[2], clarification and improvement of evaporation and condensation heat transfer phenomena in heat exchangers (evaporators and condensers)[3], design of new compressors[4], improvement of connecting pipes[5], etc. However, this development data is too detailed to be used for life cycle design to build a business strategy. On the other hand, useful indicators such as COP (coefficient of performance) do not show any relationship between design parameters, making it difficult to support decision

making.

Figure 1 shows a schematic of the prospective life cycle design of emerging technologies[6] based on seamless analysis from nm to km, using air conditioners as an example. The study of emerging technologies is divided into three major levels: the "materials and components" level (nm to mm level), the "process" level (mm to m level), and the "system" level (m to km level). At the "materials and components" level, taking air conditioners as an example, a variety of research is being conducted. On the other hand, at the "system" level, research is conducted that combines LCA, MFA, IOA and several future scenarios to predict the future, identify gaps between the vision and the predicted future, and identify the need for emerging technologies through back-casting. Computer-aided process engineering is the intermediate process-level research that plays the role of reflecting technical information in system-level analyses with appropriate granularity and precision.

In this study, computer-aided process engineering

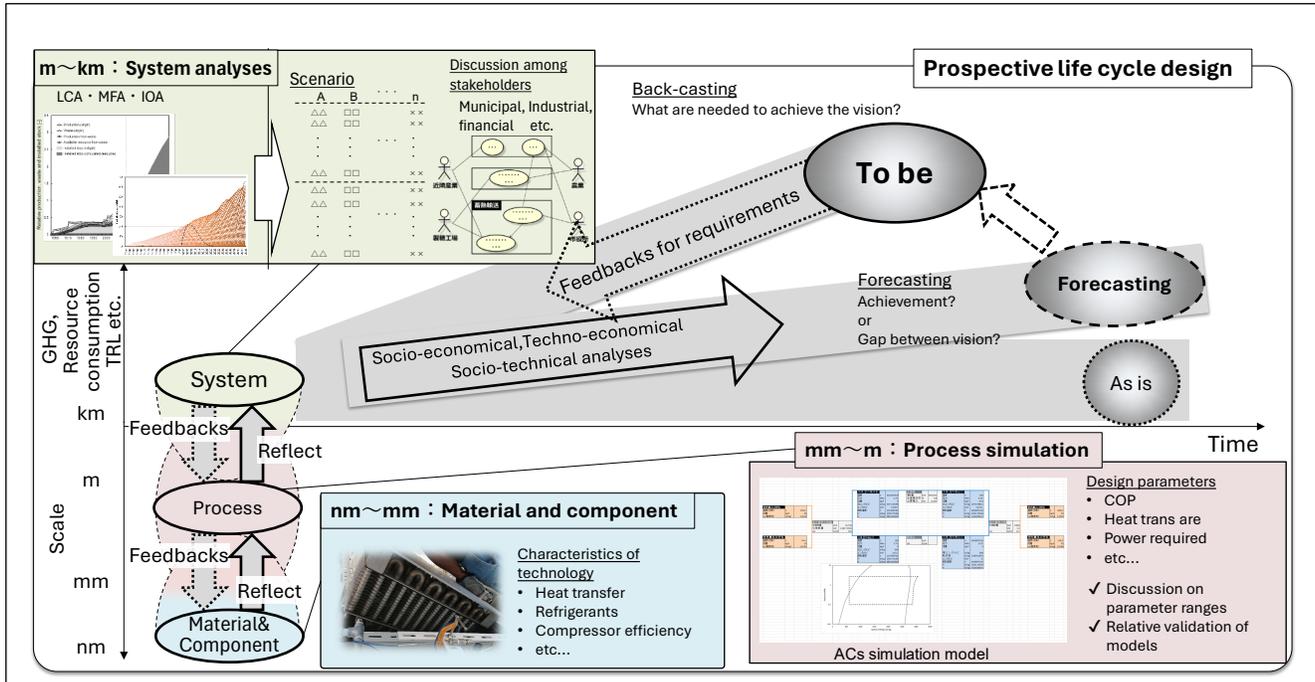


Figure 1. Schematic of prospective life cycle assessment for design by seamless analysis from nm~km

is positioned as a function that links technology development and system-level analyses, and a fundamental model combining process simulation of air conditioners, MFA, and LCA was developed to identify the effect of replacing conventional refrigerants with natural refrigerants on life cycle greenhouse gas (GHG) emissions.

MATERIAL AND METHODOLOGY

Figure 2 shows the linkage diagram among each analysis for prospective life cycle design of air conditioners. Technological data such as like heat transfer coefficient, thermophysical data of refrigerant, design of heat exchangers, efficiency of compressors and fans and the like were aggregated into the process modeling. Figure 3 shows the schematic of process flow diagram of air conditioners. A 2.2 kW air conditioner was simulated as a model machine. In the process modeling, a process flow diagram including heat exchangers for indoor and outdoor, a compressor and an expansion valve was modelled as shown in Figure 3, and for the compressor, the specific enthalpy after compression was calculated assuming an adiabatic efficiency of 90% and for the expansion valve, the refrigerant temperature after expansion was calculated assuming isenthalpy expansion. In the heat exchangers for indoor and outdoor units, the heat exchange process between refrigerants and outdoor air and indoor air was plotted on a temperature-enthalpy diagram, then the UA (overall heat transfer coefficient) values of each heat exchanger were quantified to calculate the relative change in heat exchanger size. The configuration of heat exchangers was based on a typical plate-

fin heat exchanger, the number of stages and other sizes have been determined to match the calculated heat transfer area. The refrigerant flow rate was set to give a heat exchange rate of 2.2 kW, which is the performance of the model machine. Based on the determined refrigerant flow rate, the heat exchanger geometry and the pipe length, which was assumed to be 5 m, the pressure losses for the liquid and vapour phases were calculated, respectively. The thermophysical properties of the refrigerant have been calculated using REFPROP10[7]. By using this process modeling, operating power and size of each component for conventional and natural refrigerants could be defined. These results of process simulation were reflected in the MFA and LCA.

In the MFA, statistical data on past and estimated future cooling demand were first incorporated[8,9], then the amount of air conditioners shipped was calculated by balancing the installed stock and the amount of waste estimated by Weibull distribution[10]. Two scenarios were created in which conventional refrigerants continue to be shipped from 2020 to 2050, and a scenario in which CO₂ refrigerants are introduced at the same rate as conventional refrigerants from 2030.

In this study, only climate change was considered for the midpoint impact category, since the objective of the LCA in this study is to clarify the impact of refrigerant substitution for the purpose of GWP reduction and changes in electricity emissions intensity on GHG emissions from residential air conditioners in Japan through 2050. The life cycle boundary was set as cradle to gate of conditioned air (manufacturing and operation of air conditioners). The functional unit was defined as cooling

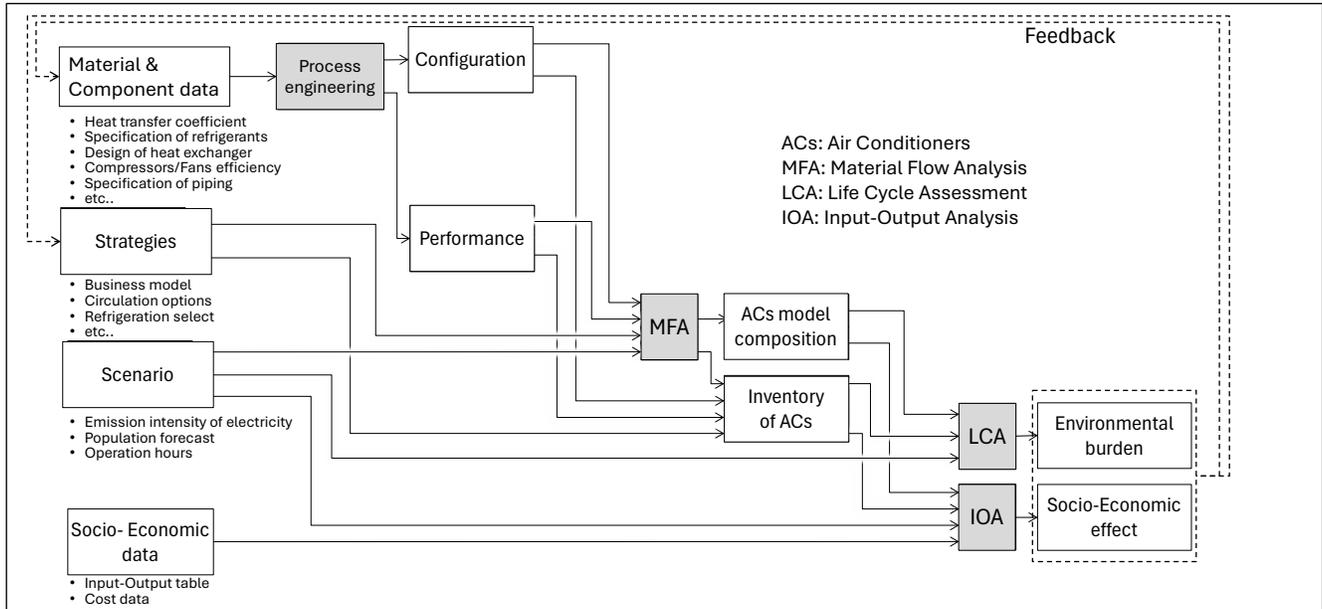


Figure 2. Linkage diagram of analyses (Process modeling, Material Flow Analysis, Life Cycle Assessment, and Input Output Analysis) for air conditioners

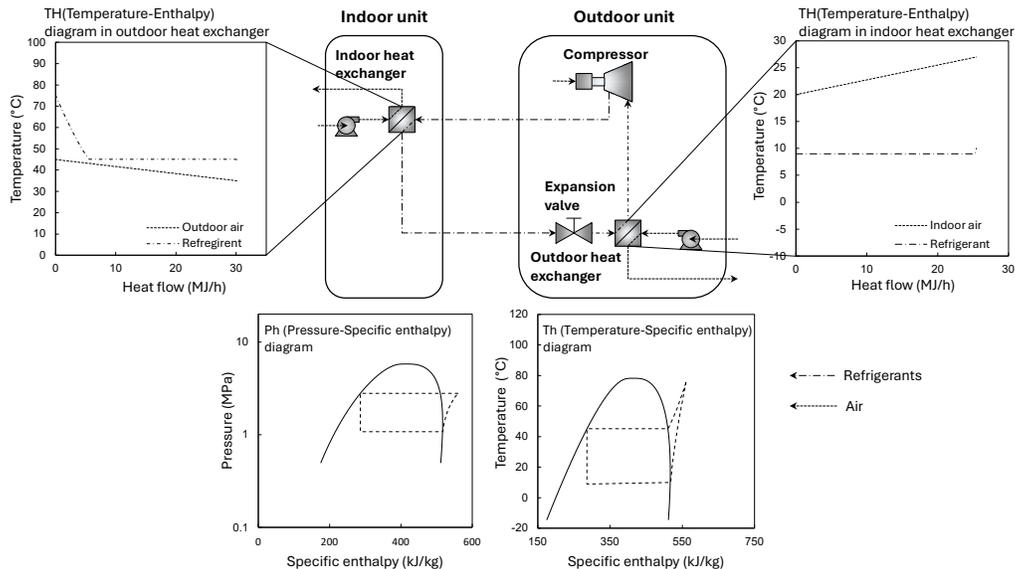


Figure 3. Schematic of process flow diagram of air conditioner

and heating by residential air conditioners in Japan through 2050. Inventory data from the manufacture of air conditioners using conventional refrigerant was set [11], and it was assumed that the environmental impact of manufacturing piping and compressors would increase in proportion to the maximum operating pressure ratio with conventional refrigerant when CO₂ refrigerant was introduced. Refrigerant leakage was set at 2% per year. Annual power consumption was estimated using performance calculated by the process modeling, annual operation hours, and the results of MFA.

The operating rate was estimated from the energy consumption of air conditioners in the residential sector in the Comprehensive Energy Statistics [12] and the

number of units in the market stock calculated by the MFA, and cooling and heating degree days were calculated, then the number of operating days per year was estimated. Annual operating hours were calculated from the operating rate and number of days from 2000 to 2020 and linearly extrapolated to 2050. For electricity emission intensity, two cases were examined: one in which Japan's electricity intensity for the past 10 years is linearly extrapolated to 2050 (almost decarbonized by 2050), and the other in which the intensity in 2020 is maintained.

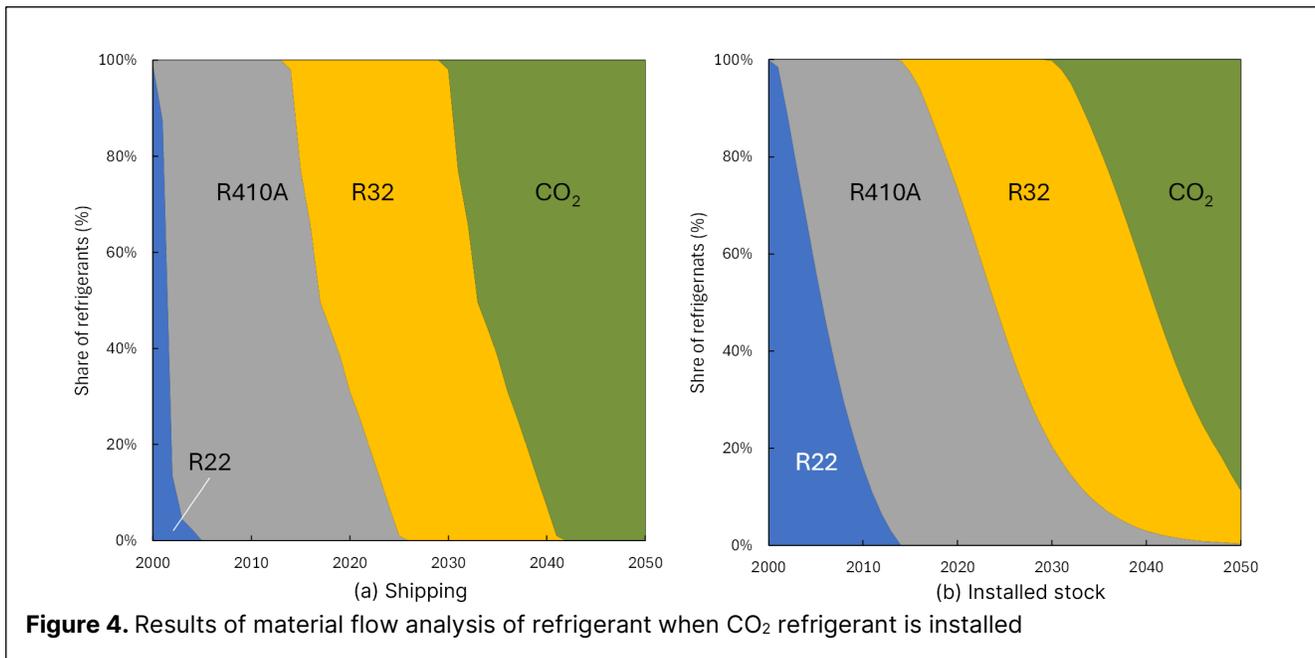


Figure 4. Results of material flow analysis of refrigerant when CO₂ refrigerant is installed

RESULTS AND DISCUSSION

Table 1 shows an example of process simulation results for an air conditioner using conventional refrigerant (R32) and CO₂ refrigerant. If an air conditioner using CO₂ refrigerant is designed to perform the same as an air conditioner using conventional refrigerant, the size of the heat exchanger will be 6 times larger when CO₂ is used as the refrigerant. On the other hand, if the heat exchanger of an air conditioner using CO₂ refrigerant is designed to be the same size as that of an air conditioner using conventional refrigerant, the COP of an air conditioner using CO₂ refrigerant is 30% worse than that of an air conditioner using conventional refrigerant.

Figure 4(b) shows the results of the MFA analysis of the installed stock of refrigerants when CO₂ refrigerant is introduced, based on the refrigerant shipment scenario in Figure 4(a). Assuming that CO₂ refrigerant shipments begin after 2030 and are introduced at the same rate as conventional refrigerants, CO₂ refrigerant will account for 90% of the total in 2050, with the remaining 10% being conventional R32 refrigerant. Using these refrigerant proportions and the results of the process simulation, an LCA up to 2050 was performed.

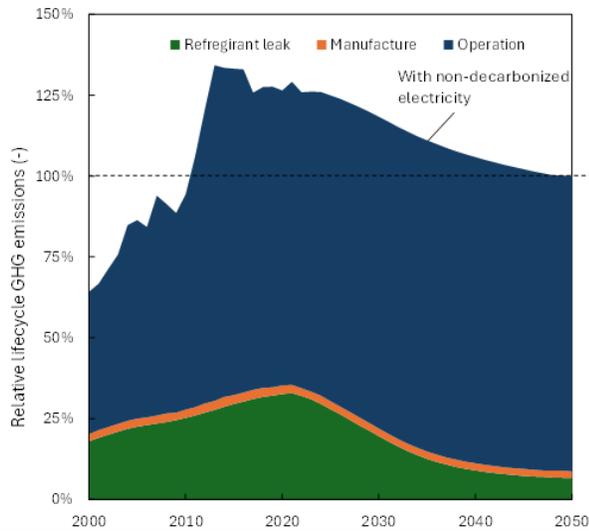
As illustrated in Figure 5(a), the results of life cycle GHG emissions from 2000 to 2050 are presented for a scenario in which conventional refrigerants continue to be used for air conditioners, and the emission intensity of electricity is equivalent to that of the year 2020. In this scenario, over 90% of the 2050 life cycle GHG emissions are derived from operations. Figure 5(b) presents the results of the life cycle GHG emissions for the electricity decarbonization scenario. A substantial decrease in GHG

emissions from operations is estimated, although the emission does not reach zero. This is attributable to the presence of residual electricity emissions intensity at 2050, estimated through linear extrapolation over the past decade, and the persistence of emissions from manufacturing and refrigerant leaks at approximately the same levels.

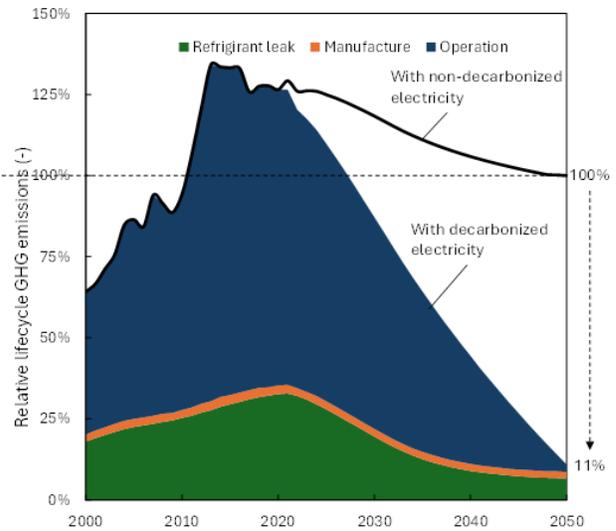
As illustrated in Figure 5(c), the life cycle GHG emissions from 2000 to 2050 for an air conditioning system designed to utilize a CO₂ refrigerant as a substitute for conventional refrigerant, with equivalent performance characteristics, are depicted. The straight lines represent the results for the non-decarbonization scenario, while the area graphs represent the results for the decarbonization scenario. In the non-decarbonization scenario, GHG emissions from operations are the predominant contributor to the total emissions, as estimated in scenarios that utilize conventional refrigerants. In the decarbonization scenario, heat exchangers will increase in size to maintain the same COP as conventional refrigerants. Consequently, GHG emissions derived from the manufacturing phase will account for a greater proportion of total emissions in 2050. In this case, circulation strategies such as heat exchanger recycling play a pivotal role.

Table 1: Results of process simulation of air conditioners utilizing conventional refrigerant (R32) and alternative refrigerant (CO₂) with two cases

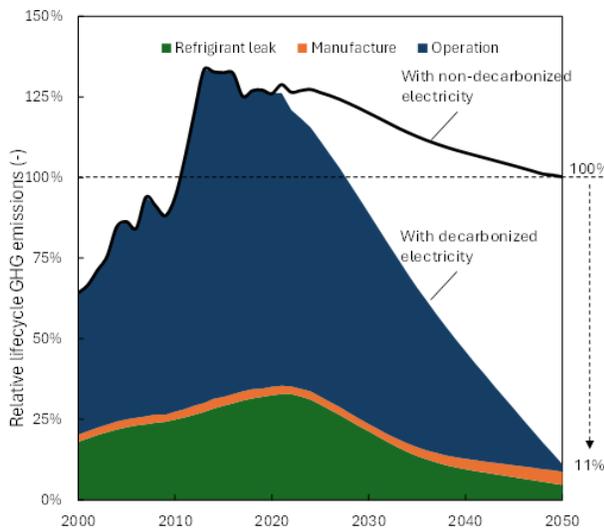
Refrigerants	Relative COP	Relative size of outdoor unit HEX
R32	100%	100%
CO ₂ (COP equivalent)	100%	574%
CO ₂ (Size equivalent)	70%	100%



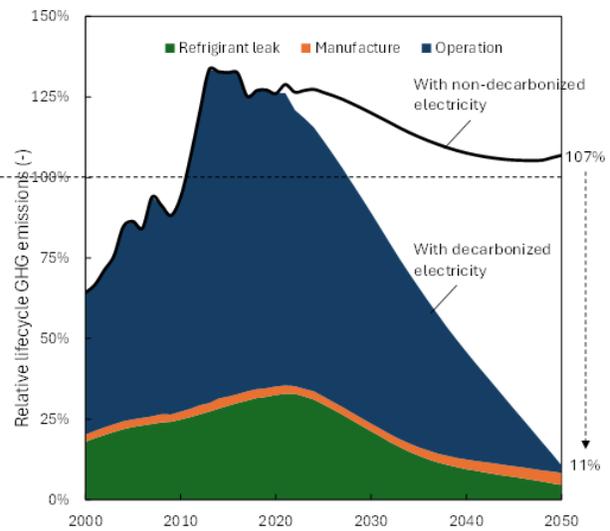
(a) Keep utilizing R32 refrigerants with non-decarbonized electricity



(b) Keep utilizing R32 refrigerants



(c) Utilizing CO₂ refrigerant with equivalent performance



(d) Utilizing CO₂ refrigerant with equivalent size of heat exchanger

Figure 5. Result of life cycle assessment

Figure 5(d) shows the life cycle GHG emissions from 2000 to 2050 for an air conditioning system utilizing CO₂ refrigerant with equivalent size of heat exchanger. In this case, the COP of the air conditioner using CO₂ refrigerant was worse than that of the air conditioner using conventional refrigerant. In the electricity decarbonization scenario, GHGs derived from electricity consumption are significantly reduced in all cases, so that even if refrigerants are replaced and heat exchangers are enlarged or electricity consumption is increased, total emissions in 2050 would be about the same level as shown in Figure 5(b),

(c), and (d), while the non-decarbonization electricity scenario results in increased electricity consumption and accompanying total GHG emissions due to lower performance for the air conditioning system utilizing CO₂ refrigerant with equivalent size of heat exchanger as shown in Figure 5(d).

In summary, the dominant factor in the life cycle GHG emissions of air conditioners is derived from electricity consumption, and to move towards carbon neutrality, reducing electricity consumption must be a priority first, and as electricity is decarbonized, the impact of

refrigerants must be considered in the future. As shown in the examples above, computational process simulation can be seamlessly integrated with MFA and LCA to reflect technological information likely to be introduced in the future, while feedback from system analyses can be used to change the strategy of the technology and discuss the feasibility of the technology. Therefore, process engineering plays an important role in prospective life cycle design in resource circulation and decarbonization strategies

CONCLUSION

In this study, computer-aided process modeling is positioned between technology development and system evaluation to promote feedback from system evaluation by reflecting technical information. The process simulation was developed to visualize the impact of refrigerant substitution by linking MFA and LCA. The results showed that the development of a process simulation that can reflect technological information has the potential to promote discussions on resource circulation and decarbonization strategies.

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